*Pest Manag Sci* **63**:276–281 (2007)



# Temporal synergism by microencapsulation of piperonyl butoxide and α-cypermethrin overcomes insecticide resistance in crop pests

Georgina Bingham,[1] Robin V Gunning,[2] Kevin Gorman,[1] Linda M Field[1] and Graham D Moores[1]*

[1]*Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*
[2]*New South Wales Department of Primary Industries, Tamworth, NSW 2340, Australia*

**Abstract: A microencapsulated formulation that gives a burst release of piperonyl butoxide (PBO) several hours before a burst release of a conventional pyrethroid can effectively overcome metabolic resistance in *Bemisia tabaci* Gennadius, *Helicoverpa armigera* (Hübner), *Aphis gossypii* Glover and *Myzus persicae* Sulzer. This increase in efficacy against resistant pests was reflected in a field trial against *B. tabaci* on cotton, eliminating the need for two treatments. The ratio between the active insecticide and the synergist was found to be crucial in reducing resistance factors.**


**Keywords:** temporal synergism; resistance; esterase; piperonyl butoxide; microencapsulation

## 1 INTRODUCTION

Insecticide resistance is a widespread phenomenon whereby insects that are subjected to intense chemical treatment may evolve mechanisms to protect themselves, and hence are able to survive and pass their resistance genes on to their offspring.[1] Resistance can then spread quickly through insect populations by virtue of short generation times and high rates of fecundity.[2] Resistance can occur either by mutations that change the target-site proteins or by changes in the insect's ability to detoxify insecticides using enzyme systems such as esterases, microsomal oxidases and glutathione-*S*-transferases (GSTs).[3] The last 10 years have seen extensive progress in understanding the molecular basis, genetics and genomics of resistance.[4,5] Many mutations that confer insensitive target sites have now been identified, and the wide range of insect microsomal oxidases, GSTs and esterases[6–8] capable of detoxifying insecticides have been elucidated. Such metabolic resistance is of great concern, as it is often capable of conferring resistance across a range of insecticides,[9] whereas target-site resistance more commonly only confers cross-resistance to other insecticides within the same chemical class, e.g. knockdown resistance (kdr),[10] or even to specific insecticides, e.g. modified acetylcholinesterase (MACE).[11]

In the peach-potato aphid, *Myzus persicae* Sulzer, at least three resistance mechanisms have evolved,[12] including that of enhanced esterase activity.[13] This mechanism is also found in the cotton aphid, *Aphis gossypii* Glover,[14,15] the tobacco whitefly *Bemisia tabaci* Gennadius[16] and the cotton bollworm *Helicoverpa armigera* (Hübner).[17] Indeed, for many of the widely used pyrethroid insecticides, resistance in field populations of several crop pest species may be primarily due to esterase isoenzymes that can hydrolyse and/or sequester the toxins.

It has long been reported that piperonyl butoxide (PBO) can 'synergise' the action of insecticides by inhibiting microsomal oxidases.[18,19] It has more recently been established that PBO can also inhibit non-specific esterases,[17] and, using laboratory bioassays, PBO was shown to potentiate pyrethroid activity against resistant laboratory strains of *B. tabaci*, *H. armigera*, *A. gossypii* and *M. persicae* where the resistance was due to metabolic factors.[20] Furthermore, in *H. armigera* and *B. tabaci*, an application of PBO at least 5 h before application of the pyrethroids α-cypermethrin and lambda-cyhalothrin resulted in effective control of highly resistant insects.[21]

Thus it would be anticipated that, in the field, pretreatment with PBO followed several hours later by a pyrethroid would also allow control of other insect pests that had evolved resistance by enhanced esterase(s) and/or microsomal oxidases. However, the need for two separate sprays of crops is not always appropriate or even financially viable; one solution has been to use the concept of insecticide microencapsulation to delay insecticide release until the factors causing resistance have been effectively

* Correspondence to: Graham D Moores, Rothamsted Research, Harpenden, Herts AL5 2JQ, UK
E-mail: graham.moores@bbsrc.ac.uk
*(Received 1 June 2006; revised version received 14 September 2006; accepted 22 September 2006)*
DOI: 10.1002/ps.1336

 *Pest Manag Sci* 1526–498X/2007/$30.00

inhibited by immediately available PBO.[22] For the present work, a formulation of PBO and pyrethroid that allows a burst release of the PBO before a second burst release of the pyrethroid some hours later has been developed on the basis of beta-cyclodextrin microencapsulation.[23] The effects of such microencapsulated formulations containing PBO and α-cypermethrin against pyrethroid-resistant *B. tabaci*, *H. armigera*, *A. gossypii* and *M. persicae* are reported here.

Following the testing of the initial microencapsulated PBO and α-cypermethrin, the formulation was optimised. It appeared that the ratio of PBO to α-cypermethrin had a direct effect on mortality – the higher the ratio of PBO, the higher was the mortality. The effects on synergism of altering the amount of PBO has previously been noted – increasing the dose of synergist enhanced the synergistic ratio when synergist and insecticide were coapplied.[24]

## 2 MATERIALS AND METHODS

### 2.1 Insects

*2.1.1* Bemisia tabaci

All strains were maintained on cotton plants (*Gossypium hirsutum* L. var. Deltapine 16 and Sicot 189) at 26 ± 2 °C with a 16:8 h light:dark photoperiod. Standard susceptible strains were SUD-S collected from the Sudan in 1978 and DARWIN collected from the Northern Territory, Australia, in 2003; B-type resistant strains were PIRGOS collected from Cyprus in 2003 and EMERALD collected from the cotton in Queensland, Australia, in 2003; CHLORAKA is a Q-type resistant strain collected from Cyprus in 2003. To ensure good insect quality, only adults less than 10 days old were used.

*2.1.2* Helicoverpa armigera

Strain HAC with elevated esterase was established from eggs collected from cotton crops in New South Wales and Queensland, Australia, in 2002/2003. The strain has been selected by exposure to insecticides in the field, including pyrethroids. A pyrethroid-susceptible strain collected from cotton at Narrabri, New South Wales, in 1982 was used for comparison.

The strains were reared on a modified Shorey Hale artificial diet at 25 ± 2 °C and 80% RH in natural light.

*2.1.3* Myzus persicae

Clones were reared on three-week-old Chinese cabbage plants (*Brassica pekinensis* (Lour) Rup. var. Wong Bok) maintained at 18 ± 2 °C with a 16:8 h light:dark photoperiod. The standard susceptible clone US1L was collected in Bottisham, Cambridge, in 1974. The resistant clone 794JZ is a highly resistant ($R_3$) variant obtained from a glasshouse at Evesham in 1982.

*2.1.4* Aphis gossypii

Clones were reared on three-week-old pumpkin plants (*Cucurbita pepo* L. var. Mammoth Gourd) maintained at 18 ± 2 °C with a 16:8 h light:dark photoperiod. Clone 171B was isolated from a population collected from the UK in 1981 and maintained as a reference susceptible. The resistant clone 1196 possessing highly elevated esterase was collected from cotton in Greece in 2003.

### 2.2 Insecticides

Two commercial α-cypermethrin 100 g $L^{-1}$ EC formulations, Fastac 10EC (BASF) and Dominex 10EC (Crop Care), were used. The PBO formulations used were PBO 30 (microemulsified in water; Endura SpA) for all bioassays except the DARWIN and EMERALD strains of *B. tabaci* where PBO 80 EC (Endura SpA) was applied.

The microencapsulated formulations were developed by Giovanna Delogu at CNR Institute of Biomolecular Chemistry, Sardinia, and by Valerio Borzatta, Endura SpA. All were suspended in distilled water containing 0.1 g $L^{-1}$ of the non-ionic wetting agent Agral® (Zeneca Agrochemicals) immediately prior to bioassays. The formulation allowed release of the PBO, followed by release of the α-cypermethrin 5 hours later. Contents of each microencapsulated formulation are shown in Table 1.

### 2.3 Leaf dip bioassays

Leaf dip bioassays were based on those previously published.[25] Leaf discs (3 cm) cut from cotton leaves were dipped into serial dilutions (1.0–0.0001 g AI $L^{-1}$) of each formulation and left to dry. The discs were then placed onto agar (1%) in petri dishes (37 mm diameter, 15 mm high), and either ten second-instar *H. armigera* larvae, ten adult aphids or 20–40 adult whiteflies (anaesthetised with carbon dioxide) were placed on the discs. Each unit was sealed with a close-fitting ventilated lid, and mortalities were assessed after 48 h at standard rearing conditions. For the PBO pretreatment, the insects were placed on leaves treated with 0.5 g $L^{-1}$ PBO and then transferred to discs treated with α-cypermethrin (Fastac EC/Dominex EC). Controls were treated with Agral only. The data were analysed using probit analysis[26] revised for

**Table 1.** Composition of microencapsulated formulations[a]

| Microencapsulation | PBO (g $kg^{-1}$) | α-Cypermethrin (g $kg^{-1}$) | PBO:α-cyp ratio |
|---|---|---|---|
| CdC51 | 230 | 190 | 1:1 |
| CdC09 | 430 | 220 | 2:1 |
| CdC45 | 190 | 70 | 2.5:1 |
| CdC43 | 220 | 50 | 4.5:1 |
| CdC27 | 310 | 50 | 6:1 |
| CdC46 | 220 | 30 | 7.5:1 |
| CdC29 | 230 | 30 | 7.5:1 |
| CdC35 | 225 | 25 | 9:1 |

[a] Each also contained 20–30 g $kg^{-1}$ of the surfactant, Soltem.

microconfiguration in the statistical programme PC PoloPlus (LeOra Software, Berkeley, CA) to generate $LD_{50}$, $LD_{95}$, $LD_{99}$ (including fiducial limits) and slope values. Control mortality was corrected using Abbott's formula.[27] The results of the probit analyses were used to generate resistance factors (RFs), calculated as the resistant $LC_{50}$ divided by the susceptible $LC_{50}$ (see Tables 2–6).

### 2.4 Field trial

Formulations of α-cypermethrin, PBO, PBO mixed with α-cypermethrin, CdC09 and a water control were sprayed onto Bollgard II cotton plants (Sicot 289b, 12–14 plants $m^{-1}$) in the field at Emerald, Queensland, Australia, using a hand sprayer calibrated for an output of 400 mL 20 $m^{-2}$, with a walking speed of 0.5 m $s^{-1}$. The conditions at the time of spraying were: wind speed below 10 km $h^{-1}$, maximum temperature 25 °C, relative humidity 40% and approximately 80% cloud cover.

There were five plots, each 2 m (two rows of cotton plants) ×10 m, with 1 m (one row) ×10 m as a buffer between the plots. Treatments were allocated in a randomised block design: plot 1, water control; plot 2, PBO 80EC; plot 3, α-cypermethrin (Dominex EC); plot 4, tank mix of PBO 80EC and α-cypermethrin (Dominex EC); plot 5, CdC09. In all plots the α-cypermethrin:PBO ratio was 1:2; α-cypermethrin was applied at the registered rate for cotton in Australia against *H. armigera* (50 g AI $ha^{-1}$).

Adult *B. tabaci* pressure was high and uniformly distributed throughout the plots.

Numbers of adult whitefly were counted on the leaves of each terminal to the fifth node prior to treatment and 24 h after treatment. The mean numbers of adult *B. tabaci*/terminal/plot and 95% confidence intervals were calculated.

## 3 RESULTS AND DISCUSSION

The results of probit analyses of leaf dip bioassay data for the two aphid species *M. persicae* and *A. gossypii* are given in Table 2. For *M. persicae* the $LC_{50}$ for α-cypermethrin on the resistant clone 794JZ was 3460 mg $L^{-1}$ compared with 5.4 mg $L^{-1}$ for the susceptible clone, giving an RF value of 640. However, when PBO was added to the α-cypermethrin, the RF was reduced to 12 and reduced still further when the PBO was either applied before the insecticide (RF = 2) or when the two were applied as a microencapsulation, allowing release of the PBO before the α-cypermethrin (RF = 3.7). A similar trend was seen for *A. gossypii* where, although the RF to α-cypermethrin for the resistant clone was lower at 12, this was still reduced by pretreatment with PBO (RF = 0.5) or microencapsulation (RF = 0.6). Thus, for both aphid species, the microencapsulated formulation was equally potent to the pretreatment, and they both led to a significant reduction in the resistance factor, resulting in the α-cypermethrin being as effective as against the susceptible clone.

A similar effect was seen in *H. armigera*, where a resistant strain (Australia HAC) with an RF of 86 was reduced to 50 when PBO was applied with α-cypermethrin as a mixture, and to complete sensitivity when the PBO was microencapsulated with the pyrethroid (Table 3).

For *B. tabaci* a resistant strain, PIRGOS, with B-type esterase, had a very high RF of 6830 when treated with α-cypermethrin (Table 4), but this was reduced to 137 when PBO was mixed with the insecticide,

**Table 2.** Results of probit analyses on leaf dip bioassay data for two aphid species *Myzus persicae* and *Aphis gossypii*[a]

| Treatment | Species/strain | *N* | $LC_{50}$ (mg $L^{-1}$) | 95% FL | Slope (±SE) | df | $\chi^2$ | RF |
|---|---|---|---|---|---|---|---|---|
| α-Cypermethrin | *M. persicae* | | | | | | | |
| | US1L (S) | 260 | 5.4 | 2.2–12.5 | 0.44(±0.07) | 24 | 13.5 | 1 |
| | 794JZ (R) | 270 | 3460.0 | 340–290 000 | 0.24(±0.06) | 25 | 19.9 | 640 |
| | *A. gossypii* | | | | | | | |
| | 171B (S) | 260 | 5.2 | 3.2–8.4 | 0.91(±0.1) | 24 | 10.8 | 1 |
| | 1196 (R) | 260 | 62.9 | 27.1–199 | 0.47(±0.07) | 24 | 10.8 | 12 |
| 0.5 g $L^{-1}$ PBO + α-cypermethrin mix | *M. persicae* | | | | | | | |
| | 794JZ (R) | 270 | 62.3 | 24.1–235 | 0.44(±0.07) | 25 | 27.1 | 11.6 |
| | *A. gossypii* | | | | | | | |
| | 1196 (R) | 260 | 5.6 | 3.0–10.3 | 0.65(±0.08) | 24 | 6.7 | 1.1 |
| 0.5 g $L^{-1}$ PBO treatment | *M. persicae* | | | | | | | |
| 5 h before α-cypermethrin | 794JZ (R) | 302 | 10.9 | 7.3–16.2 | 1.07(±0.01) | 25 | 9.6 | 2 |
| | *A. gossypii* | | | | | | | |
| | 1196 (R) | 260 | 2.4 | 1.6–3.7 | 1.16(±0.12) | 24 | 9.9 | 0.5 |
| CdC35 | *M. persicae* | | | | | | | |
| | 794JZ (R) | 260 | 19.7 | 10.5–19.9 | 0.86(±0.09) | 24 | 35.0 | 3.7 |
| | *A. gossypii* | | | | | | | |
| | 1196 (R) | 260 | 3.0 | 2.0–4.4 | 1.24(±0.13) | 24 | 17.6 | 0.6 |

[a] *N* = number of insects tested; $LC_{50}$ = pyrethroid concentration needed to kill 50%; FL = fiducial limits; SE = standard error; df = degrees of freedom; $\chi^2$ = chi-square value; RF = resistance factor; S = susceptible strain; R = resistant strain.



*Pest Manag Sci* **63**:276–281 (2007)
DOI: 10.1002/ps

**Table 3.** Results of probit analyses on leaf dip bioassay data for first-instar *Helicoverpa armigera* (notation as in Table 2)

| Treatment | Strain | *N* | $LC_{50}$ (mg $L^{-1}$) | 95% FL | Slope (±SE) | df | $\chi^2$ | RF |
|---|---|---|---|---|---|---|---|---|
| α-Cypermethrin | Susceptible | 180 | 5.8 | 5.5–6.2 | 3.0(±0.4) | 5 | 1.4 | 1 |
| | Australian HAC (R) | 180 | 500 | 230–1100 | 1.1(±0.2) | 5 | 5.2 | 86 |
| 0.5 g $L^{-1}$ PBO + α-cypermethrin mix | Australian HAC (R) | 180 | 290 | 150–550 | 1.5(±0.2) | 5 | 6.6 | 50 |
| CdC09 | Australian HAC (R) | 180 | 3.9 | 2.6–5.6 | 2.3(±0.2) | 5 | 0.2 | 0.6 |

**Table 4.** Results of probit analyses on leaf dip bioassay data for *Bemisia tabaci* (notation as in Table 2)

| Treatment | Strain | *N* | $LC_{50}$ (mg $L^{-1}$) | 95% FL | Slope (±SE) | df | $\chi^2$ | RF |
|---|---|---|---|---|---|---|---|---|
| α-Cypermethrin | SUD-S (S) | 898 | 2.8 | 2.4–3.3 | 2.3(±0.2) | 24 | 11.8 | 1 |
| | PIRGOS (B-type R) | 919 | 19100 | 4120–740000 | 1.0(±0.25) | 24 | 29.4 | 6834 |
| | CHLORAKA (Q-type R) | 910 | 1540 | 957–3360 | 1.4(±0.22) | 25 | 4.6 | 551 |
| 0.5 g $L^{-1}$ PBO + α-cypermethrin mix | PIRGOS | 518 | 384 | 290–547 | 2.1(±0.23) | 24 | 26.8 | 137 |
| | CHLORAKA | 682 | 1210 | 749–2400 | 0.86(±0.1) | 25 | 1.9 | 433 |
| 0.5 g $L^{-1}$ PBO treatment | PIRGOS | 544 | 1.6 | 1.3–1.9 | 2.3(±1.0) | 24 | 10.6 | 0.6 |
| 5 h before α-cypermethrin | CHLORAKA | 919 | 8.8 | 7.7–10.0 | 3.7(±0.3) | 25 | 6.6 | 3.1 |
| CdC35 | PIRGOS | 484 | 3.6 | 2.6–4.9 | 2.3(±0.21) | 24 | 43.8 | 1.3 |
| | CHLORAKA | 508 | 12.1 | 8.9–16.7 | 2.0(±0.21) | 13 | 16.1 | 4.3 |

**Table 5.** Results of probit analyses on leaf dip bioassay data for *Bemisia tabaci* strains DARWIN (susceptible) and EMERALD (B-type R) (notation as in Table 2)

| Treatment | Strain | *N* | $LC_{50}$ (mg $L^{-1}$) | 95% FL | Slope (±SE) | df | $\chi^2$ | RF |
|---|---|---|---|---|---|---|---|---|
| α-Cypermethrin | Darwin, native (S) | 360 | 0.084 | 0.072–0.099 | 3.5(±0.3) | 5 | 1.02 | 1 |
| | Emerald (B-type R) | 360 | 70 | 40–120 | 1.1(±0.2) | 5 | 8.9 | 833 |
| 0.5 g$L^{-1}$ PBO + α-cypermethrin mix | Emerald | 360 | 12 | 8–20 | 0.93(±0.21) | 5 | 5.8 | 143 |
| CdC09 | Emerald | 360 | 0.41 | 0.17–0.95 | 1.9(±0.2) | 5 | 2.3 | 4.8 |

and to 0.6 and 1.3 for the PBO pretreatment and microencapsulation respectively. For another *B. tabaci* strain, CHLORAKA, with Q-type esterase, the RF for α-cypermethrin was 551 and the addition of PBO to the insecticide mix had little effect on the resistance factor (433). However, when PBO was used as a pretreatment, the RF for α-cypermethrin was reduced to 3.1 and for the microencapsulation to 4.3, so clearly temporal synergism with PBO still proved to be very effective. Similarly, EMERALD had an RF of 833, reduced to 143 with a mix of PBO and α-cypermethrin, and with CdC09 (microencapsulation) the RF was reduced further to 4.8 (Table 5).

These results have demonstrated that, in all four insect species, resistance resulting from enhanced metabolic activity can be effectively overcome when PBO inhibits the enzymes prior to the active ingredient being applied (in the PBO pretreatment) or released (in the microencapsulation). In the leaf dip bioassays of *M. persicae, A. gossypii* and *B. tabaci* (Tables 2 and 4) the microencapsulated formulation (CdC35) contained PBO and α-cypermethrin at a ratio of 9:1, whereas for the *H. armigera* assay using CdC09 (Table 3) the ratio was 1:2. To see whether this ratio is important in obtaining maximum efficacy of the product, a range of formulations were tested against the PIRGOS strain of *B. tabaci* (Table 6). When the RFs were plotted against the ratio of PBO to α-cypermethrin (Fig. 1) it was revealed that the RF values were inversely proportional to this ratio. Thus, greater mortality of the resistant whitefly was obtained when higher proportions of PBO were present in the formulation.

Having established that microencapsulated formulations of PBO and α-cypermethrin mimic the pre-spray

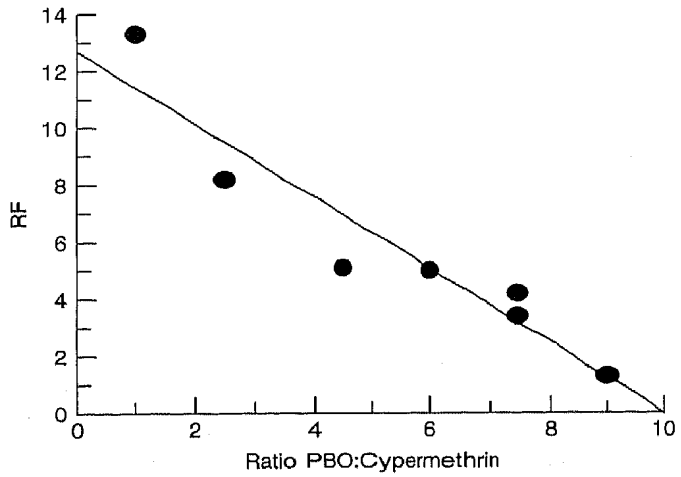


**Figure 1.** Resistance factors for *Bemisia tabaci* strain PIRGOS (B-type R) plotted against the PBO:α-cypermethrin ratio in a microencapsulated formulation (correlation coefficient = 0.944).

**Table 6.** Results of probit analyses on leaf dip bioassay data for *Bemisia tabaci* strain PIRGOS (B-type R) (notation as in Table 2)

| Treatment | PBO:α-cypermethrin ratio | *N* | $LC_{50}$ (mg $L^{-1}$) | 95% FL | Slope (±SE) | df | $\chi^2$ | RF |
|---|---|---|---|---|---|---|---|---|
| CdC51 | 1:1 | 631 | 37.2 | 30.4–45.3 | 2.06(±0.17) | 25 | 3.68 | 13.3 |
| CdC45 | 2.5:1 | 530 | 22.3 | 18.9–27.9 | 2.5(±0.24) | 24 | 15.35 | 8.2 |
| CdC43 | 4.5:1 | 491 | 14.2 | 11.5–17.0 | 2.89(±0.32) | 24 | 9.21 | 5.1 |
| CdC27 | 6:1 | 696 | 13.9 | 12.1–15.7 | 4.4(±0.48) | 24 | 0.2 | 5 |
| CdC46 | 7.5:1 | 518 | 9.38 | 7.32–12.1 | 1.46(±0.11) | 24 | 19.2 | 3.4 |
| CdC29 | 7.5:1 | 520 | 11.7 | 9.9–14.1 | 3.3(±0.35) | 24 | 27.53 | 4.2 |
| CdC35 | 9:1 | 484 | 3.58 | 2.64–4.9 | 2.26(±0.21) | 24 | 43.8 | 1.3 |

regime and were very effective at restoring the efficacy of the pyrethroid against insects with esterase-based resistance in leaf dip bioassays, the concept was extended to determine whether similar increases in efficacy could be replicated in field situations. The chosen test system was a field crop of cotton growing in Australia and containing high numbers of Australian B-type *B. tabaci*. The results of the trial are given in Fig. 2. The pre-/post-spray numbers of *B. tabaci* were not statistically different in any treatment, except for the PBO/α-cypermethrin mixture (in which the mean number of whitefly fell from 9 to 5) and the microencapsulated formulation which gave almost complete control of the insects (12 whitefly to 1).

This study has demonstrated that metabolic-based resistance capable of conferring very high resistance factors can be overcome using temporal synergism. The delay required to allow optimum inhibition of the resistance-associated enzymes can be imparted by bespoke formulations that enable the release of PBO prior to a burst release of insecticide several hours later. Such microencapsulated formulations restored susceptibility to several crop pests, and in at least one, *B. tabaci*, this effect could be repeated in the field. The concept of targeting the defence mechanism(s) of pest species by means of temporal synergism offers the potential for restoration of insecticides abrogated by metabolic resistance.

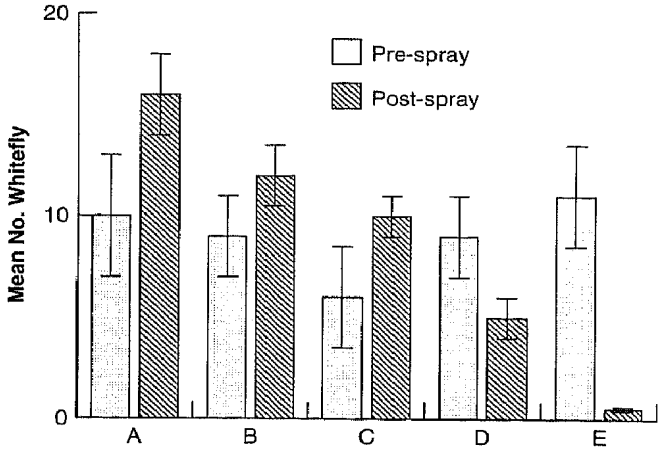


**Figure 2.** Mean numbers of adult *Bemisia tabaci* present in treatment plots in the field trial (see Section 2.4). Treatments: A = control, water; B = PBO, 500 mg $L^{-1}$ spray; C = α-cypermethrin, 250 mg $L^{-1}$ spray; D = PBO 500 mg $L^{-1}$ and α-cypermethrin 250 mg $L^{-1}$ spray; E = CdC09, PBO 500 mg $L^{-1}$ and α-cypermethrin 250 mg $L^{-1}$ microencapsulated formulation.

## ACKNOWLEDGEMENTS

The work was partially funded by Endura SpA, Bologna, Italy, and the Cotton Research and Development Corporation, Australia. The authors would like to thank Dr Carlotta Gobbi and Dr Valerio Borzatta of Endura SpA and Dr Giovanna Delogu of the CNR Institute of Biomolecular Chemistry, Sassari, Italy, for their support in the preparation of the microencapsulated compound samples. Rothamsted Research receives grant-aided support from the Biotechnology and Biological Sciences Research Council of the United Kingdom.

## REFERENCES

1 Plapp FW and Wang TC, Genetic origins of insecticide resistance, in *Pest Resistance to Pesticides*, ed. by Georghiou GP and Saito T. Plenum Press, New York and London, pp. 47–70 (1979).
2 Denholm I, Insecticide resistance: an avoidable pest management problem. *Asp Appl Biol* 17:239–246 (1988).
3 Baillie AC, Insecticides: how they act and why they fail, in: *Combating Resistance to Xenobiotics*, ed. by Ford MG, Holloman DW, Khambay BPS and Sawicki RM. Ellis Horwood, Chichester, UK, pp. 228–238 (1987).
4 Oakehott JG, Horne I, Sutherland TD and Russell RJ, The genomics of insecticide resistance. *Genome Biol* 4:202 (2003).
5 ffrench-Constant RH, Daborn PJ and Le Goff G, The genetics and genomics of insecticide resistance. *Trends Gen* 3:163–170 (2004).
6 Scott JG and Wen ZM, Cytochromes P450 of insects: the tip of the iceberg. *Pest Manag Sci* 57:958–967 (2001).
7 Enyati AA, Ranson H and Hemmingway J, Insect glutathione transferases and insecticide resistance. *Ins Mol Biol* 14:3–8 (2005).
8 Wheelock CE, Shan G and Ottea J, Overview of carboxylesterases and their role in the metabolism of insecticides. *J Pestic Sci* 30:75–83 (2005).
9 Devonshire AL and Moores GD, A carboxylesterase with broad substrate specificity causes organophosphorus, carbamate and pyrethroid resistance in peach potato aphids (*Myzus persicae*). *Pestic Biochem Physiol* 18:235–246 (1982).
10 Martinez-Torres D, Foster SP, Field LM, Devonshire AL and Williamson MS, A sodium channel point mutation is associated with the resistance to DDT and pyrethroid insecticides in the peach-potato aphid, *Myzus persicae* (Sulzer) (Hemiptera: Aphidae). *Ins Mol Biol* 8:339–346 (1999).
11 Andrews MC, Callaghan A, Field LM, Williamson MS and Moores GD, Identification of mutations conferring insecticide resistance-insensitive AChE in the cotton-melon aphid *Aphis gossypii* Glover. *Ins Mol Biol* 13:555–561 (2004).

12 Field LM and Foster SP, Amplified esterase genes and their relationship with other insecticide resistance mechanisms in English field populations of the aphid, *Myzus persicae* (Sulzer). *Pest Manag Sci* **58**:889–894 (2002).
13 Devonshire AL and Moores GD, Detoxification of insecticides by esterases from *Myzus persicae* – is hydrolysis important? in *Enzymes Hydrolysing Organophosphorus Compounds*, ed. by Reiner E, Aldridge W and Hoskin FCG. Ellis Horwood, Chichester, UK, pp. 180–192 (1989).
14 Wang KY, Lui TX, Yu CH, Jiang XY and Yi MQ, Resistance of *Aphis gossypii* (Homoptera: Aphidae) to fenvalerate and imidacloprid and activities of detoxification enzymes on cotton and cucumber. *J Econ Entomol* **95**:407–413 (2002).
15 Han Z, Moores GD, Denholm I and Devonshire AL, Association between biochemical markers and insecticide resistance in the cotton aphid *Aphis gossypii* Glover. *Pestic Biochem Physiol* **62**:164–171 (1998).
16 Gunning RV, Byrne FJ, Conde BD, Connely MI, Hergstrom K and Devonshire AL, First reported resistance of a B-biotype *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) in Australia. *J Aust Entomol Soc* **34**:116 (1995).
17 Gunning RV, Moores GD and Devonshire AL, Inhibition of resistance-related esterases by PBO in *Helicoverpa armigera* (Hemiptera: Amphididae), in *Piperonyl Butoxide. The Insecticide Synergist*, ed. by Jones DG. Academic Press, London and San Diego, pp. 215–226 (1998).
18 Brattsten LB and Metcalf RL, The synergistic ratio of carbaryl with piperonyl butoxide as an indicator for the distribution of multifunction oxidases in the *Insecta*. *J Econ Entomol* **63**:101–104 (1970).
19 Perry AS and Buchnor AJ, Studies on microsomal cytochrome P-450 in resistant and susceptible houseflies. *Life Sci* **9**:335–350 (1970).
20 Young S, Gunning RV and Moores GD, The effect of PBO on pyrethroid resistance-associated esterases in *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae). *Pest Manag Sci* **61**:397–401 (2005).
21 Young S, Gunning RV and Moores GD, Effect of pretreatment with piperonyl butoxide on pyrethroid efficacy against insecticide-resistant *Helicoverpa armigera* (Lepidoptera: Noctuidae) and *Bemisia tabaci* (Sternorrhyncha: Aleyrodidae). *Pest Manag Sci* **62**:114–119 (2006).
22 UK Patent 0309773.0. Rothamsted Research Ltd and Minister for Agriculture and Fisheries in the State of New South Wales, compositions and methods for preventing or reducing resistance of insects to insecticides, pct/gb03/01861. (2005).
23 Patent WO 2005/039287. Endura S.P.A., Formulation of a synergistic insecticidal composition as a cyclodextrin-complex, WO 2005/039287 A2 (2005).
24 Pap L, Arvai G, Bertok B, Kuruczne Ribai Z and Bakonyvari I, Comparative evaluation of new synergists containing a butynyl-type synergophore group and piperonyl butoxide derivatives. *Pest Manag Sci* 57:186–190 (2001).
25 Cahill M, Byrne FJ, Gorman K, Denholm I and Devonshire AL, Pyrethroid and organophosphate resistance in the tobacco whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae). *Bull Entomol Res* **85**:181–187 (1995).
26 Finney DJ, *Probit Analysis*, 3rd edition. Cambridge University Press, London (1972).
27 Abbott WS, A method for computing the effectiveness of an insecticide. *J Econ Entom* **18**:265–267 (1925).